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640 Gbit/s Optical Signal Processing

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Abstract: Techniques for 640 Gbit/s generation, demultiplexing, clock recovery, add/drop multiplexing, wavelength conversion, transmission, channel identification and timing jitter tolerant switching is described. Various switching materials are explored, such as HNLF, SOA, chalcogenide, and PPLN.

OCIS codes: (190.4360)Nonlinear optics, devices; (060.2330) Fiber optics communications

1. Introduction

The single channel bit rate has continuously increased in deployed optical transmission systems and networks, reaching 10–40 Gb/s in today's commercially available systems. With the appearance of new technologies for optical transmitters and receivers operating near 100 Gb/s [1], ultra fast signal processing becomes increasingly relevant. For ultra-high-speed serial data operating at rates above 100 Gbit /s, signal processing becomes increasingly challenging and only optical signal processing seems possible. For almost twenty years now, optical time division multiplexing (OTDM) has been explored as a possible route to generate high bit rates in the optical domain, but there has hitherto been no market penetration. There are several reasons for this, and apart from market circumstances, we believe the most important one is the lack of good practical solutions for essential functionalities. With the introduction of internet video transmission, the bit rates have exploded and internet exchange office congestion is becoming a real limitation. Therefore there is once again a need for basic research in solutions to congestion problems. There is currently a great focus on 100 Gb/s Ethernet (100 GE), and in 5-10 years from now, in Internet exchange stations one may have several 100 GE lines, which may need to be transmitted to the same destination, and to avoid congestion, it may be beneficial to employ an ultra-fast optical Ethernet multiplexing. This would result in an optical 1000 GE, or 1 Terabit/s Ethernet, 1 TE. In fact, at OFC 2008, plenary speaker Bob Metcalfe, inventor of the Ethernet, professed that 1 TE will be needed soon, and that it is essential to conduct fundamental research on new technologies that can carry this burden, since current technologies cannot [2]. Whether 1 TE will be best created serially or in parallel is an open question, but to answer it, it is necessary to conduct research on high-speed serial communications. One great concern with the parallel technologies developed so far is their massive power consumption. Serial solutions combined with circuit switched networks may help to reduce the power consumption. In any possible future serial-type network scenario one could envisage, a number of essential network functionalities would be needed, including channel identification and add/drop multiplexing. 640 Gbaud symbol rates (pulse rates) has so far been demonstrated as the highest pulse rate carrying data by a few groups worldwide, first in [3] and then most notably in [4], so 1 Tbaud in itself is a challenge.

Here we will present some recent demonstrations of several of the mentioned high-speed functionalities, namely techniques for 640 Gb/s demultiplexing, transmission, clock recovery, wavelength conversion and add/drop multiplexing, as well as channel identification and finally touch on the topic of stability and jitter tolerance. We aim at demonstrating that there are solutions for the required functionalities in a high-speed TDM system. Several materials and components will also be shown to be able to operate at high speed. Here we will touch upon highly non-linear bulk-type fibres (HNLF), photonic crystal fibres (PCF) and more compact devices as periodically poled Lithium Niobate (PPLN), chalcogenide waveguides and semiconductor optical amplifiers (SOAs).

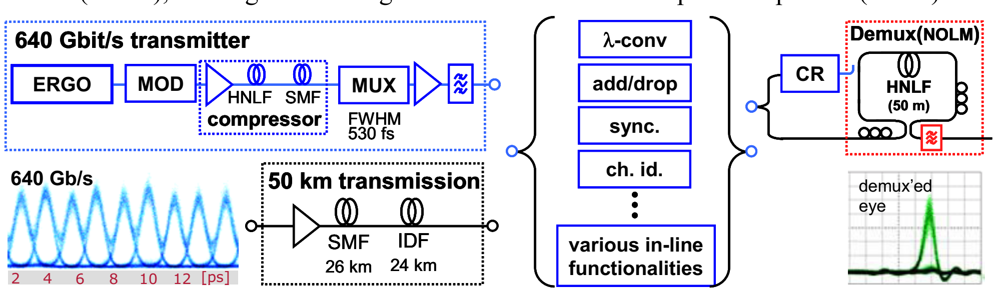

Figure 1. Schematic of 640 Gb/s communication system with a lab-type transmitter and receiver. In a more realistic network scenario, the transmitter would be very different to this set-up. Various important in-line functionalities are also sketched.

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2. 640 Gb/s demultiplexing

Most 640 Gb/s demux demonstrations, as the initial one in 1998 [5], involve HNLF. A non-linear optical loop mirror (NOLM) is a popular choice [4-7] due to the inherent interferometer arm match of the Sagnac interferometer geometry. HNLF is a mature commercial product from several companies and is very suitable for this application. Other types of fibre have also been used, though only for 160 Gb/s demonstrations. This goes for photonic crystal fibre [8] or bismuth-oxide fibre [9]. HNLF has also been used in a Kerr switch at 640 Gb/s [10]. Recently, compact components have been used to demultiplex 640 Gb/s. Filtering-assisted (f-a) XPM in an SOA was demonstrated at 640 Gb/s in [11]. Chalcogenide waveguides have been shown to operate at 160 Gb/s [12] and also at 640 Gb/s [13].

3. 640 Gb/s transmission and clock recovery

Ultra-high-speed clock recovery has proven to be exceptionally challenging, and only very recently was 640 Gb/s reached allowing for full transmission demonstrations [14]. In [14], f-a XPM in an SOA was used, as in [15] at 320 Gb/s. This was followed by a second 640 Gb/s demonstration [16]. In [16-17], a PPLN device was used, relying on the $\chi^{(2)}$–mediated process of sum-frequency generation, which is truly ultra-fast and not depending on any carrier recovery. Adding a base rate phase mark on one channel and then filter that out for clock recovery has also proven viable at 320 Gb/s and simultaneously allowing for channel identification [18]. This should scale to 640 Gb/s.

4. 640 Gb/s wavelength conversion

Four wave mixing (FWM) in HNLF was used to convert at 640 Gb/s from the C to the L band and back again in [6]. The 20 dB bandwidth of the 640 Gb/s data was about 20 nm, so it would be difficult to stay in the C band when converting with FWM. In [19], Raman-enhanced XPM was used to convert a 16 nm 20 dB bandwidth 640 Gb/s data signal to a lower wavelength within the C band, see Fig. 2. Very recently FWM was shown to enable 640 Gbit/s wavelength conversion in the C-band [30]. These three demonstrations so far are the only reported successful 640 Gb/s wavelength conversion experiments, and they all utilise HNLF. An SOA with f-a XPM has been shown to operate up to 320 Gb/s [20], but due to carrier recovery issues this does not seem set for 640 Gb/s just yet.

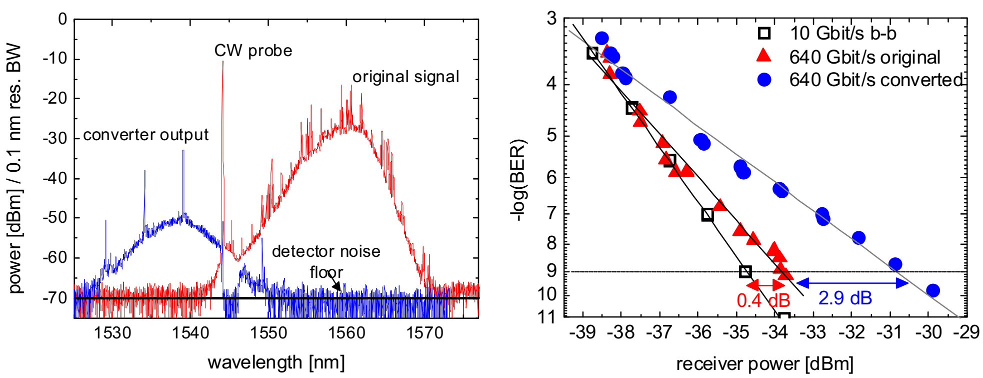

Figure 2. 640 Gbit/s wavelength conversion based on Raman-enhanced XPM in HNLF [20].

5. 640 Gb/s add/drop multiplexing

Recently, simultaneous add and drop was demonstrated in a NOLM at 320 Gb/s [21], and is now upgraded to 640 Gb/s [22]. In [23], 640 Gb/s add/drop is performed in a non-linear polarisation-rotating fibre loop, see Fig. 3. [21-23] utilise HNLF. In [9], a 1 m bismuth oxide fibre is used at 160 Gb/s. A HNLF-based Kerr switch is used in [24] and a NOLM in [25], both at 160 Gb/s with eye characterisation at 320 Gb/s

6. Pulse shaping for increased timing tolerance/stability

Flat-top pulses have been proven to increase the timing tolerance of high-speed switches and enable retiming. Various approaches have been followed, such as the optical Fourier transform technique [26], using super-structured fibre Bragg gratings [27] or using optical differentiation based on detuned long-period gratings for 640 Gb/s [28]. To further enhance stability of a fibre switch, polarisation independence can be invoked in a NOLM simply by choosing the right switching power [29]. PM fibres and temperature-stabilisation also help a great deal.

7. Conclusion

This paper has provided highlights of ultra-high-speed signal processing demonstrations, in order to demonstrate that solutions do exist for many essential 640 Gb/s functionalities.

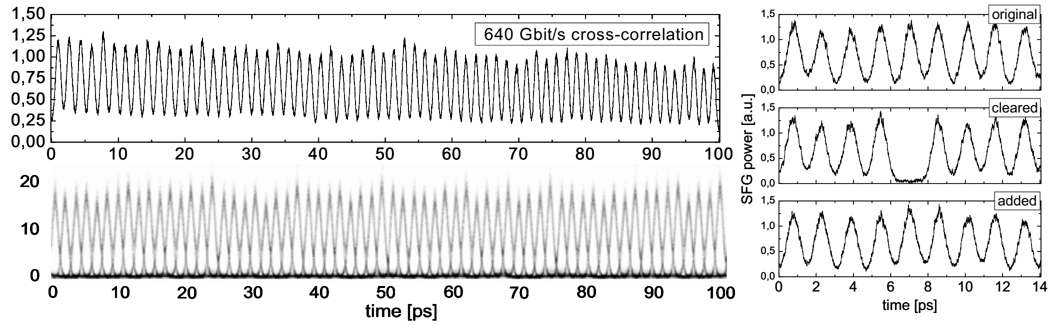

Figure 3 .640 Gbit/s add/drop multiplexing in a non-linear polarisation-rotating fibre loop [23].

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